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HIGH-PRECISION EARTH ROTATION AND EARTH-MOON DYNAMICS

Lunar Distances and Related Observations

Edited by O. Calame

VOLUME 94

PROCEEDINGS

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PROCEEDINGS OF THE 63rd COLLOQUIUM OF THE
INTERNATIONAL ASTRONOMICAL UNION,
HELD AT GRASSE, FRANCE, MAY 22–27, 1981

Edited by

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A SERIES OF BOOKS ON THE RECENT DEVELOPMENTS
OF SPACE SCIENCE AND OF GENERAL GEOPHYSICS AND ASTROPHYSICS
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VOLUME 94
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INTRODUCTION

Depuis le 21 Juillet 1969, une ère nouvelle s'est ouverte dans notre connaissance du système Terre-Lune, avec l'accumulation de mesures de distances ultra-précises aux réflecteurs laser déposés sur la surface lunaire. Au cours des recherches effectuées à partir de cette nouvelle technique, il s'est très vite avéré que le champ d'applications était considérable et qu'il fallait complètement réviser certaines théories antérieures. Avec des observations au niveau de quelques centimètres, il n'est plus possible d'étudier des phénomènes isolément et, quel que soit le pôle d'intérêt fixé, il est nécessaire aussi d'étudier conjointement les autres aspects du système. Très vite, il est alors apparu que les recherches potentielles relatives à ce type d'observations ne se bornaient pas seulement aux applications lunaires mais pouvaient recouvrir un domaine plus vaste en Astronomie, Géodésie, Géophysique, Cosmologie, etc... C'est ainsi qu'est né le programme international EROLD, avec comme but plus spécifique l'étude de la rotation terrestre, mais avec des aspects connexes liés en particulier à la dynamique du système Terre-Lune dans son ensemble. Il était alors naturel de faire le bilan, à un niveau élevé, de ces années de recherches dans cette nouvelle phase de la connaissance.

Par ailleurs, d'autres types de techniques modernes ont également vu le jour durant cette dernière décennie, avec entre autres applications la détermination de la rotation de la Terre. Après la campagne initiale d'observations MERIT, il était utile de fournir aussi une première opportunité de rassembler et discuter les résultats scientifiques obtenus dans ce domaine à partir des nouvelles méthodes. Ainsi, à la suite d'un atelier de travail, se tenant également à Grasse (du 18 au 21 Mai 1981) et portant sur les aspects techniques et opérationnels, la première session de ce Colloque était consacrée plus spécialement à l'étude de la rotation de la Terre sur elle-même. Les suivantes traitaient des divers problèmes scientifiques concernant particulièrement la Géodynamique, les théories des mouvements de la Lune et les systèmes de références.

Après plusieurs années d'engagement presque total aux activités de télémétrie Laser-Lune et de dynamique du système Terre-Lune dans ses aspects variés, je fus très honorée et réjouie de pouvoir organiser et mener à bien ce Colloque (N°63) sous le haut patronage de l'Union

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Astronomique Internationale (UAI/IAU), tenu à Grasse (France), du 22 au 27 Mai 1981. En outre, l'Association Internationale de Géodésie (AIG/IAG) et le COSPAR s'associaient également pour parrainer cet évènement.

Le Comité d'Organisation Scientifique regroupait :

- *O. Calame (Président)*
- *Yu. L. Kokurin*
- *P. J. Morgan*
- *I. I. Mueller (Représentant de l'AIG)*
- *J. D. Mulholland (Représentant du COSPAR)*
- *P. J. Shelus*

Ce Colloque était soutenu financièrement par plusieurs organismes (UAI, GRGS, CERGA et CNES). Qu'ils soient ici tous remerciés de leur contribution, ainsi que les autorités locales de leur participation et intérêt à cette manifestation.

Enfin, je souhaite que les compte-rendus, ici publiés, tout en ne pouvant refléter que partiellement la dimension et l'intérêt des échanges de vue parmi les participants, puissent représenter un document de travail fructueux pour les voies de recherches futures dans ces domaines.

Odile Calame
Octobre, 1981.

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SETH CARLO CHANDLER, LL.D. (1846-1913)

Discoverer of the Earth's free nutation; author of over 200 astronomical papers; inventor of the almucanter; pioneer in astronomical telegraphic codes; Editor, The Astronomical Journal (1896-1909); Member and Watson Medalist (1895), U. S. National Academy of Sciences; Gold Medal (1896), Royal Astronomical Society

SETH CARLO CHANDLER AND THE OBSERVATIONAL ORIGINS OF GEODYNAMICS

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Geodynamics can be defined as the study of the motions of Earth with respect to its own center of mass and three locally-inertial directions. These motions include rotations of the whole Earth, as well as episodic, cyclic and secular deformations of the crust, and internal fluid circulations. Geodynamics is still largely an observational science, since there is yet no satisfactory theory to account for several of the most interesting of these motions. The observational aspects of geodynamics are basically astronomical, since the most obvious effects of terrestrial rotation and deformation (excepting of course occasional cataclysmic deformations) are seen as variations in the apparent positions of celestial bodies, as observed from the surface of the mobile, non-rigid Earth.

The advance of science is conditioned by a usually-polite tug-of-war between observation and theory. Sometimes, however, one becomes so impressed with the structure and/or past success of a mathematical theory that he loses sight of the fact that the only aspect of the "real world" that is real is the corpus of observed phenomena. When that happens, scientific progress can be impeded. Such was the case in 1890 with the rotation of the Earth -- and perhaps is still the case.

One may, we think, date the birth of geodynamics from the first observational evidence of systematic effects of Earth's non-rigidity on its rotation. Ironically, the discoverer is virtually a forgotten man, often misrepresented as a dilettante, his later discoveries of complex time-variability in the free nutation still meeting dogmatic resistance from theorists. Ninety years after his initial discovery, Seth Carlo Chandler remains in the same position in which he then found himself -- rejected on theoretical grounds, despite the fact that the observations support his conclusions. Even as he was right in 1891, he is very possibly right now.

Chandler was dismissed by Munk and Macdonald (1960) as a "wealthy merchant" from New York, who doubled as an amateur astronomer. Nothing

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could be farther from the truth. Chandler began his astronomical career very early. In 1860, when he was only 14 years old, he worked as a computing aide to Benjamin Pierce at Harvard College. After graduation from high school, he became an assistant to B. A. Gould, founder of the Astronomical Journal, then busily involved in developing a network of astronomical stations for the U. S. Coast Survey (later to become the Coast and Geodetic Survey, today known as the National Ocean Survey, NOAA).

It was a particularly exciting period in the history of geodetic astronomy. The advanced technology of telegraphy presented the possibility to transfer accurate time across continents and indeed, by undersea cable, even between continents. Gould and his colleagues exploited this new fact by establishing a unified network, nationwide across the United States, of longitude stations tied directly to the prime meridian at the Royal Greenwich Observatory. Young Chandler soon immersed himself in this work and joined the Coast Survey as a regular employee in 1864. Computation was his primary work, but he was also trained both as recorder and observer on the astro teams; he applied these latter skills later in establishing stations at Calais, Maine, and New Orleans, Louisiana. Thus, the years that Chandler might have spent in college, studying the achievements of others, were instead used to learn by participation at the leading edge of current technology. While this meant that he could not immediately gain academic "credentials" (He was eventually awarded the degree of Doctor of Laws by DePauw University in 1891), he clearly gleaned a comprehensive knowledge of the machines and mathematics of geodetic astronomy, and he developed an intense interest in the subject that would remain with him for the rest of his life.

Gould left the Coast Survey in 1870 to oversee development of the newly-founded observatory at Cordoba, Argentina, and he invited his protégé to join him. But Chandler had proposed marriage to Miss Caroline Herman, and he divined that astronomy was no way to provide a comfortable living to a young family. He found his mathematical skills eagerly put to use in the insurance industry, with a definitely non-astronomical salary. He seems to have done quite well as an actuary during seven years in New York, for at the end of this time he was able to return to his native Boston as a "consulting actuary". In 1881, he found the spare time to resume his astronomical research, to which he directed an enormous reserve of energy. For several years, he was associated with the Harvard College Observatory, following which he worked as an independent scholar. During his life, he published over two hundred scientific papers, with at least two still in incomplete manuscript at the time of his death in 1913.

Dr. Chandler was not a single-track scientist. During his career, he made contributions in several different parts of astronomy. Apart from his work in longitude determination under Gould, he computed comet orbits, providing an impressive proof of the identity of comet 1889d with Lexell's comet of 1770. Working with J. Ritchie at Harvard, he devised perhaps the first telegraphic code for rapid distribution of new discoveries to observatories, the predecessor to the present International Astronomical Union Telegram Bureau. He worked extensively on variable stars, producing several important catalogues. His analysis of Algol established the possibility that "the winking star" is a triple system. The list goes on, but the work for which Seth Chandler was best known in his lifetime -- and which is of most interest in the present context -- is his discovery of the free nutation of Earth's axis that bears his name: the Chandler motion or Chandler wobble.

The possibility of a free nutation of Earth's axis of figure about its rotation axis was recognized by Leonhardt Euler as a mathematical consequence of his newly-developed theory of rotation of rigid bodies. Since such a motion is not dependent on predictable external forces, he was unable to estimate an amplitude, but he saw that the frequency was controlled by the moments of inertia of the Earth. Euler predicted a period of ten months for what has come to be called the Eulerian nutation. Over the next century, several attempts were made to observe such an effect in stellar positions. All were unsuccessful, although English Astronomer Royal G. B. Airy claimed significance for one of Simon Newcomb's studies -- a claim that Newcomb did not second. As we now know, there is no 10-month free nutation.

Chandler took up the problem, but with an important difference: he consciously and explicitly abandoned any preconceptions of period based on theory, undertaking to let the observations speak for themselves. During his Harvard association, he had invented an ingenious instrument for observing stellar positions, the Almucantar, and he supplemented the data from professional observatories with his own, using this device. In 1891, he stunned the astronomical establishment with an analysis (Chandler 1891a, 1891b) showing a significant polar motion with a period of 427 days. The 40% difference from Euler's prediction created a controversy that had overtones of professional snobbism; it was just in this period, and particularly at Harvard, that the rift between salaried astronomers and "amateurs" was in full furor. In any event, several prominent theorists suggested that either Chandler's observations or his analyses were faulty, because it was unthinkable that Euler could have made such a gross error. It was, after all, a beautiful and elegant theory. Chandler (1891b) was unimpressed: "I am not much dismayed by the argument of conflict with dynamic laws, since all that such a phrase means, must refer merely to the existent state of the theory ..." Not only that, but the offending period would not go away. All was reconciled when Newcomb (1891) found a way to explain the discrepancy between 306 and 427 days as a consequence of the "fluidity of the oceans" and the "elasticity of the Earth". The details of Newcomb's explanation were wrong, but the force of his prestige convinced those who were unmoved by the experimental data. Since "Eulerian nutation" is an obvious misnomer for something so different from Euler's prediction, the term "Chandler motion" soon became current.

It is tempting to consider the rejection of the observational analysis by Chandler's contemporaries as an aberration of the time or of the protagonists. The second half of the story is not yet ended, however. Chandler did not retire on his discovery, but continued for several years to refine his analyses, trying to understand what the real Earth was doing. He soon saw that the nutation period was not constant, and he was drawn first to suggest (Chandler 1892a) that it had increased secularly throughout the 19th century. Unchastened by recent experience, Newcomb (1892) greeted this idea with the sweeping statement, "... *any* variation of the period is in such direct conflict with the laws of dynamics that we are entitled to pronounce it impossible." Both men were wrong. Chandler noted in reply (1892b) that his observational results had already forced one drastic revision of dynamical theory, so any authoritarian appeal to "the laws of dynamics" was specious. Further analysis showed, however, that the variation was not secular, but at least partly due to phase interference between multiple frequencies. Chandler (1892c) proposed that the dominant 14-month period was modulated by an annual component, a result that stands confirmed today. The combination of Chandler and annual frequencies does indeed result in a polar motion whose radius and period are variable. This seems to have been accepted by Newcomb, who participated in the recommendation that the discoverer receive the Watson Medal of the U.S. National Academy of Sciences, in 1895, for the ensemble of his work on the rotation of the Earth; the citation refers specifically to the variability of the free nutation. It seems clear that Newcomb intended that his objection of 1892 apply only to the secular variation.

Chandler was still not satisfied with his residuals, and he continued to investigate the fine structure of the observations, convinced that the apparent complexity represented real physics. He eventually concluded that the 14-month periodicity was not a simple one, but was composed of a major peak at 428 days and a much smaller one at 436 days (Chandler 1901), and that "the angular velocity and radius of motion have some inverse relationship" (Chandler 1902). In a rare display of dogmatic consistency, the defenders of "the laws of dynamics" once again rejected a chandlerian analysis on the grounds of conflict with theory, and they continue to do so today. Munk and Macdonald claim that Newcomb's 1892 declaration suffices to refute the dual-frequency model, or any other real variation in period, even though Newcomb's remark was disproven as a generality by the annual term. Dickman (1981) rejects any "sudden and temporary change" in the Chandler frequency as "geophysically unreasonable", a phrase that has zero scientific content. To add insult to injury, Dickman wrongly attributes the dual-frequency model of Chandler to someone else, 67 years later.

The observational data still support Chandler, not the theory. Carter (1981a) has shown that 63 years of homogeneous ILS polar motion data indicate a significant correlation between the amplitude of the motion and the variation in the beat period. The frequency variation of about 0.3-0.6 cycles per year increase per arc second decrease in the polar motion amplitude corresponds to Chandler's "inverse relationship" of 1902. Furthermore, based on his two frequencies, Chandler predicted that their interference would produce a sharp minimum in the apparent period of the free nutation of 415 days, which he thought would occur around 1910. In his recent study, Dickman found a sharp minimum which corresponds to an equivalent period of 418 days in the 1920's, which Carter (1981b) has noted to be "not incongruous with Chandler's findings." If Chandler were alive today, he would surely find a trenchant way to suggest that, if the theories cannot yet accommodate the observations, then the theorists may not yet have found the real Earth.

Seth Carlo Chandler was honored properly in his lifetime, including election to the National Academy of Sciences, the Watson Medal, and the Gold Medal of the Royal Astronomical Society. On the death of his mentor Gould in 1896, he became Editor of the Astronomical Journal, a post that he retained until 1909, when ill health forced him to step down. Now, after so many decades of neglect and worse, recognition of his contributions to science is returning. His scientific correspondence has recently been archived on microfilm by the American Institute of Physics, and some of his personal instruments have been added to the collection of the Museum of American History, a branch of the Smithsonian Institution of Washington. On the scientific side, the study of the rotation of the Earth is now entering upon a new era, with the application of instruments and techniques of unprecedented accuracy, just as we approach the centenary of Chandler's initial studies in the subject. For these reasons, we feel that it would be most fitting that the MERIT Earth rotation observing campaign of 1983-84 be dedicated as a scientific memorial to this most remarkable and persistent man, a professional scientist in every sense of the word save one, the founder of observational geodynamics.

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